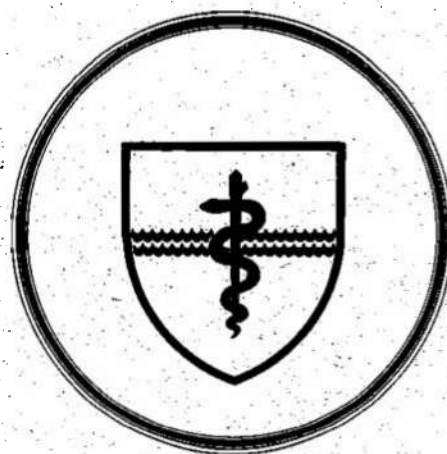


NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.



REPORT NUMBER 1043

NOISE EXPOSURE IN HYPERBARIC ENVIRONMENTS

by

Paul F. Smith

Naval Medical Research and Development Command
Research Work Unit M0096.002-1047

Released by:

W. C. Milroy, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

October 1984

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A handwritten signature in dark ink, appearing to read 'W Milroy', is written over the printed name.

William C. Milroy, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

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SUMMARY PAGE

THE PROBLEM

To evaluate the applicability of existing hearing conservation standards to noise exposure in hyperbaric environments.

FINDINGS

The audiometric function is changed in hyperbaric helium-oxygen environments. Specifically, existing data and theoretical considerations indicate that in helium-oxygen diving situations hearing sensitivity is poorer than at the surface for frequencies up to 2000 to 4000 Hz. Data, but not theory, show that hearing sensitivity is also depressed in compressed air environments. For both breathing gasses data and theory agree in indicating that existing hearing conservation standards are needlessly conservative for dry diving environments.

APPLICATION

These findings contribute toward the establishment of hearing conservation standards for exposure to noise in dry diving environments.

ADMINISTRATIVE INFORMATION

This investigation was conducted under NMRDC Research Work Unit M0096.002-1047. The report was originally submitted for review in January 1984 and approved for publication on 6 February 1984. It was presented at the OCEANS '84 Conference and Exposition sponsored by the Marine Technology Society and the IEEE Ocean Engineering Society in Washington, D.C., 10-12 September 1984 and later appeared in the Proceedings of OCEANS, pp 521-526.

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ABSTRACT

New developments in diving systems and underwater tools are increasing the extent of noise exposure of divers. The need for effective, but appropriate hearing-conservation regulations has been recognized. This paper presents a review of the physical and physiological factors which determine auditory sensitivity in hyperbaric environments and the effects of noise on divers. Experimental evidence on hearing and noise exposure in hyperbaric environments is also reviewed. In general, it is essential that noise measurements made in diving chambers and helmets take into account the characteristic impedance of the breathing gas used in specific operations. Failure to do so results in a gross overestimation of the noise intensity to which divers are exposed. Further, changes which occur in the functioning of the external ear tend to reduce overall auditory sensitivity at frequencies below 6000 Hertz thus providing some protection from the effects of noise. However, auditory sensitivity may be enhanced at the higher frequencies (6000 to 12000 Hertz) with consequences that are as yet unknown. Such changes in auditory function are not due to physiological changes but are attributable wholly to the environment in which the diver is functioning. Theory and existing evidence clearly indicate that the application of current hearing-conservation standards for normo-baric conditions to hyperbaric environments is inappropriate.

CORRIGENDUM

In section 2. Physical considerations the expression

$$I = p^2 z$$

and following subscripted expressions should read

$$I = p^2 / z$$

NOISE EXPOSURE IN HYPERBARIC ENVIRONMENTS

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Abstract

New developments in diving systems and underwater tools are increasing the extent of noise exposure of divers. The need for effective, but appropriate hearing-conservation regulations has been recognized. This paper presents a review of the physical and physiological factors which determine auditory sensitivity in hyperbaric environments and the effects of noise on divers. Experimental evidence on hearing and noise exposure in hyperbaric environments is also reviewed. In general, it is essential that noise measurements made in diving chambers and helmets take into account the characteristic impedance of the breathing gas used in specific operations. Failure to do so results in a gross overestimation of the noise intensity to which divers are exposed. Further, changes which occur in the functioning of the external ear tend to reduce overall auditory sensitivity at frequencies below 6000 Hertz thus providing some protection from the effects of noise. However, auditory sensitivity may be enhanced at the higher frequencies (6000 to 12000 Hertz) with consequences that are as yet unknown. Such changes in auditory function are not due to physiological changes but are attributable wholly to the environment in which the diver is functioning. Theory and existing evidence clearly indicate that the application of current hearing-conservation standards for normobaric conditions to hyperbaric environments is inappropriate.

1. Introduction

In an earlier paper, the impact of applying hearing-conservation standards for noise exposure in normobaric environments to dry diving environments was discussed (1). In this paper, the physical and physiological bases for developing new standards tailored for specific diving environments is presented. It is important that the issues discussed here be resolved because the Navy is currently drafting a hearing-conservation standard for hyperbaric operations and that standard may become the bases for future regulatory action by other governmental agencies. A recent ruling by the U.S. Navy Medical Command that existing hearing-conservation standards be applied without modification to dry hyperbaric conditions has already severely affected

The opinions expressed in this paper are those of the author and do not necessarily represent the official views of the U.S. Navy Department.

the development of the Navy Mark-14 diving system and, as shown in my previous paper, if promulgated as a hearing-conservation standard, would severely limit the amount of time per day that divers could use certain hand-held tools.

2. Physical considerations

Sound is transmitted from a source, such as a noisy valve or tool, to the ear through a medium. For a given noise source, the amount of sonic energy arriving at the ear is greatly influenced by the characteristic impedance (Z) of that medium. In a gaseous medium, Z is a function of the product of the density (d) of the medium and the sonic velocity (c) of that medium. That is,

$$Z = dc.$$

The velocity of sound changes very little as pressure increases, so the ratio of the impedance of hyperbaric air to the impedance of normobaric air may be estimated directly from the ratio of the two densities. Since the density of a gas varies directly with pressure, as pressure increases, the characteristic impedance of compressed air increases. The velocity of sound does vary with the composition of breathing mixtures and must, therefore, be taken into account in computing Z for specific gas mixtures.

Although sound pressure is the most commonly reported measure of stimulus levels in studies of hearing, it is the intensity of a sound that is the important variable in determining the effects of sound on hearing. The intensity (I) of a sound is related to the sound pressure (P) as

$$I = P^2 Z$$

Intensity level (IL) in decibels (dB) is obtained by

$$IL = 10 \log(I_1/I_0)$$

with I_0 being the "reference intensity", usually 10-12 Watts per square meter. An equivalent expression is

$$IL = 10 \log((P_1^2 Z_1)/(P_0^2 Z_0)), \text{ or}$$

$$IL = 10 \log(P_1^2/P_0^2) + 10 \log(Z_0/Z_1)$$

where the subscripts refer to the media in which the

measurements are made.

A corresponding expression in terms of sound pressure level (SPL) in decibels is

$$SPL = IL = 20 \log(P_1/P_0) + 10 \log(Z_0/Z_1)$$

where P_0 is the reference sound pressure, usually 20 microPascal.

When all sound measurements are made in the same medium ($Z_1=Z_0$) then the last term in the previous two equations disappears. If, however, sounds to be compared are measured in media with different characteristic impedances the last term, which I shall refer to as the "correction" for impedance, may have a significant value and must be retained.

If two Sound Pressure Levels (both of which are referenced to the same P_0) are compared by subtraction ($SPL_2 - SPL_1$) then

$$SPL_2 - SPL_1 = (20 \log(P_2/P_0) + 10 \log(Z_0/Z_2)) - (20 \log(P_1/P_0) + 10 \log(Z_0/Z_1))$$

which may be written as:

$$SPL_2 - SPL_1 = 20 \log P_2 - 20 \log P_1 + 10 \log Z_1 - 10 \log Z_2 - 20 \log P_0 + 20 \log P_0 - 10 \log Z_0 + 10 \log Z_0.$$

Thus, the reference pressure P_0 and the reference impedance Z_0 cancel, leaving

$$SPL_2 - SPL_1 = 20 \log(P_2/P_1) + 10 \log(Z_1/Z_2).$$

Note that the correction for impedances remains.

What this means is that it is not permissible to compare sound pressures measured at the surface with sound pressures measured at depth without including the $10 \log(Z_1/Z_2)$ correction. In order to avoid ambiguity, when the correction for impedances is applied in the comparison of sound pressure levels measured in different media the result should be referred to as a difference in intensity levels.

As an example of the importance of the correction for impedance, a sound pressure level of 92 dB at 10 ATA in compressed air corresponds in intensity to a sound pressure of:

$$92 + 10 \log .1 \\ = 82 \text{ dB measured at the surface.}$$

From the foregoing it will be understood that the intensity of a sound varies directly with sound pressure squared and inversely with the characteristic impedance of the medium. Thus, for a constant SPL, the intensity of a sound will decrease as ambient pressure increases. If sound pressure thresholds are measured at the surface and at several different depths and the results compared without correcting for impedances, then the changing relationship between sound pressure and intensity, which

occurs in the absence of any changes in the ear itself, would make it appear as though the diver were experiencing reduced auditory sensitivity. The greatest apparent loss of auditory sensitivity (in terms of SPL) would be observed near the surface. For each doubling of ambient pressure in a given medium, a 3 dB drop in apparent auditory sensitivity would be observed.

3. Physiology

Since research tends to show that at least for the range of ambient pressures investigated to date, cochlear functioning is not affected by hyperbaric conditions, I will confine my analysis here to the external ear canal and the middle ear cavity. Most authors attribute apparent changes in auditory sensitivity in hyperbaric environments to changes in the functioning of these structures, especially the middle ear cavity. Furthermore, since research on hearing in hyperbaric environments is usually done using earphones I will only consider in passing effects that the head and torso have on free field hearing sensitivity.

The ear canal (the external acoustic meatus) is a short, narrow tube which is somewhat oval in cross section (6.5 by 9 mm) and not altogether uniform along its length (23 to 27 mm). In normobaric air it is broadly resonant at about 4000 Hertz (Hz) such that the sound pressure at the ear drum (tympanic membrane) is somewhat higher over the 1000 to 8000 Hz frequency band than the sound pressure at the entrance to the canal (2). At 4000 Hz the gain is about 10 to 12 dB but it is less at other frequencies.

However, the ear canal is not the only structure external to the middle ear influencing auditory sensitivity. The sound pressure acting on the ear drum of an observer in a free sound field (and, probably also in a diffuse field) is about 15 to 17 dB higher over the frequency range of 2000 to 5000 Hz than is the pressure acting on a small microphone at the location of the eardrum with the observer absent. This effect is due to diffraction, reflection, and resonances of the torso, the mass of the head, and the pinna as well as the ear canal and it is a function of the relationship of the wavelengths of the impinging sound and the size of those structures (3). It is important to note that these transfer characteristics are "wavelength" dependent not necessarily "frequency" dependent.

The middle ear cavity (tympanic cavity) is normally filled with the ambient atmosphere. It is quite irregular in shape and communicates with oral-nasal cavity (the pharynx) through the Eustachian tube. Furthermore, there are a large number of openings into very small spaces called the mastoid cells. Its volume is generally estimated to be about 1.5 cubic centimeters. This cavity is surrounded for the most part by bony tissue except for the tympanic membrane, two membranes separating it from the cochlea and some soft tissue surrounding the opening to the Eustachian tube.

The effect of the middle ear cavity on the input impedance of the ear is negligible in the normal human ear (4,5,6). The middle ear cavity does ex-

hibit resonance, however, at about 2000 Hz and may reduce sensitivity below its resonance frequency by about 1 dB (7). The most important functions of the middle ear cavity may be to dampen and broaden the resonance of the ear canal (2) from which it is separated by the tympanic membrane which provides a baffle for the ossicular chain (8), and to provide a "clean room" for the ossicular chain.

The ossicular chain, which transmits the vibrations of the tympanic membrane to the oval window membrane of the cochlea, is located in the middle ear cavity. This is an almost purely mechanical arrangement in which the coupling of adjacent units in the chain is very close and lightly damped although subject to modification at high sound levels. Two small muscles, the tensor tympani and the stapedius muscle moderate the transmission properties of the ossicular chain under some circumstances. No mechanism (apart from changes in middle ear cavity compliance) by which the functioning of the ossicular chain would be altered by hyperbaric conditions has been suggested.

To recapitulate, in a healthy ear the ear canal seems to provide some gain to the auditory system over the frequency range of 500 to 5000 Hz, and the middle ear cavity has a negligible effect on sensitivity except that it may impair hearing slightly at frequencies below about 2000 Hz.

4. Expected operation of the ear in dry diving environments.

At the surface, in air, the resonance frequency of the ear canal is about 4000 Hz. In a 95%, 5% HeO₂ gas mixture at 30 ATA the velocity of sound is about 2.6 times that in normobaric air hence, the resonance frequency of the ear canal would shift to about 10,400 Hz. Figure 1., which is presented only for the purpose of illustration, shows the effect of the ear canal pressure transfer function on hearing sensitivity at 1 ATA (surface) and the lower frequency portion of the expected canal transfer function in a 95%, 5% HeO₂ environment at 30 ATA (depth). As shown in the bottom curve in Fig. 1 the effect of the shift in resonance frequency is to reduce sensitivity at 4000 Hz by 8 to 10 dB and increase sensitivity by about the same amount at 8000 Hz. Since the ear canal resonance is quite broad, however, the effect would not be more than 10 dB at either frequency and smaller still at other frequencies. As we shall see, this change in resonance frequency of the external auditory meatus does not, by itself, explain existing data on hearing in hyperbaric environments.

Associated with the change in resonance frequency of the ear canal is a change in its characteristic impedance (the characteristic impedance of the ambient environment divided by the cross-sectional area of the canal) which varies directly with the characteristic impedance of the ambient medium. This effect, of course, works in the direction of maintaining an impedance match between the ear and the medium.

The loss of auditory sensitivity at depth is usually attributed to changes in the impedance or the resonance frequency of the middle ear cavity

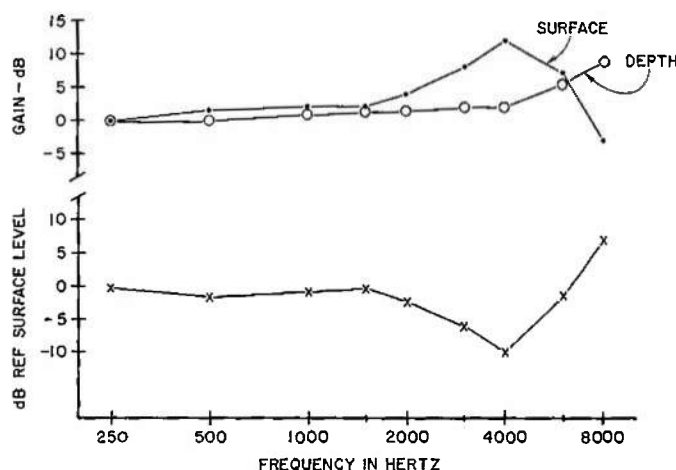


Figure 1. Sound pressure transformation from the entrance of the external auditory meatus to the tympanic membrane in air at 1 ATA (surface) and in 95% He, 5% O₂ at 30 ATA (depth) and the effect on auditory sensitivity at depth with respect to auditory sensitivity at the surface. Surface data abstracted from Wiener and Ross (2).

under pressure (9,10,11). It is supposed that since the middle ear cavity is filled with hyperbaric gas which is more dense than surface air, then the input impedance of the ear would be altered, creating a conductive type hearing loss. That the sensitivity of the cochlea is not altered at depth is shown by the relative invariance of bone-conduction thresholds with depth at least to 11 ATA in compressed air (10) and 30 ATA in HeO₂ (11).

The middle-ear cavity resonance frequency would also be shifted upward in an HeO₂ atmosphere to about 5200 Hz at 30 ATA in HeO₂ but it would not be affected appreciably in compressed air. Also, the acoustic compliance of the middle ear cavity (which is determined by the volume of the gas in the cavity divided by the product of the density of that gas and the square of the sonic velocity in that gas) would be progressively diminished as depth (density) increased in a given medium as has been pointed out by several authors. Contrary to the expectation that this diminished compliance would produce a conductive type hearing loss (9,10,11), the change in compliance with depth is exactly in the direction required to maintain a match between the characteristic impedance of the increasingly dense medium and the input impedance of the ear. In the normal situation, however, the impedance of the middle ear is largely determined by the resistance provided by the cochlear contents. The middle ear cavity has a rather small effect on the input impedance of the ear measured at the tympanic membrane (4,5,6), and there is little reason to believe that the compliance of a healthy middle ear cavity has an important role in hearing in hyperbaric gas with the exception that in an HeO₂ environment it may reduce sensitivity by about 1 dB below the cavity resonance frequency which would be shifted

to about 5000 Hz at 30 ATA.

5. Psychoacoustics in hyperbaric gas.

As indicated earlier, the ear canal and the middle ear are not the only determinants of auditory sensitivity. Shaw has shown that the acoustic pressure gain at the tympanic membrane attributable to wavelength dependent processes (resonance, diffraction, etc.) accounts for much of the shape of the auditory sensitivity function (3). As an approximation, let us assume that the total minimum audible field (MAF) sensitivity of the human ear is accounted for by such sound pressure transfer functions. All other effects such as changes in middle ear cavity compliance are ignored. What, then, should we expect to see when auditory thresholds are measured in hyperbaric environments?

Fig. 2 shows the American Standards Association MAF threshold curve for surface conditions (surface) (abstracted from Licklider (8)) and the expected MAF function at 30 ATA in HeO₂. The lower curve in Fig. 2. is the arithmetic difference between the two curves at audiometrically important frequencies. This curve shows how hearing thresholds at 30 ATA in HeO₂ would differ from threshold levels at the surface.

If measurements are made in a free field, the shift in the gain function for the body and the canal effects would produce a reduction in sensitivity of 20 dB or so in the 250 to 500 Hz frequency region. In the 1000 to 3000 Hz frequency region, auditory sensitivity would be reduced by 8 to 10 dB compared to surface threshold values. In the 4000 to 6000 Hz region there occurs a transition from impaired to improved sensitivity at depth with auditory sensitivity being up to 25 dB better at 16,000 Hz at depth than at the surface.

We can now draw a hypothetical audiogram for a diver with perfectly normal hearing at 30 ATA on HeO₂. Assume that the data are reported as in the second column of Table I without correcting for the impedance of the medium (a practice which seems universal, unfortunately). The results are as follows:

At 4000 Hz and below substantial loss of sensitivity (16 to 31 dB), greatest below 1000 Hz,

Above 4000 Hz hearing sensitivity at depth is about the same as at the surface.

The data corrected for impedance are shown in the last column of Table 1. Thus, this very rough model which is based solely on changes in the resonance frequency of the external auditory meatus and other wavelength dependant transfer functions predicts reduced auditory sensitivity of up to 19 dB in the 250 to 4000 Hz frequency region and enhanced sensitivity at 6000 Hz and higher frequencies for a dive to 30 ATA on HeO₂.

The model predicts little or no change in auditory sensitivity for dives on compressed air.

I shall now compare the results of experiments on hearing under hyperbaric conditions with the results above.

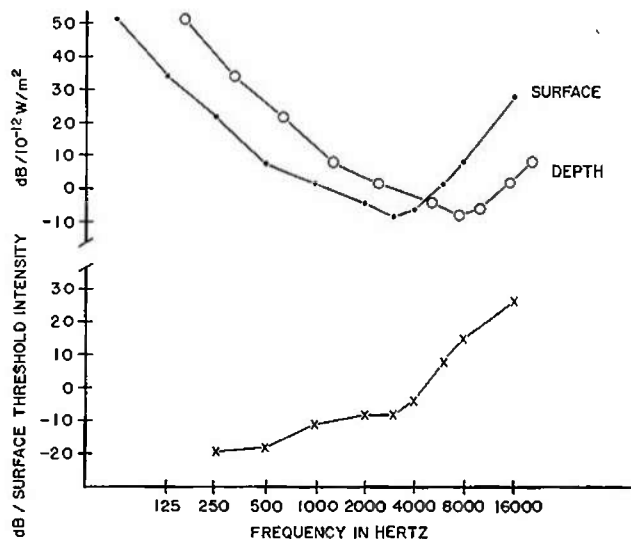


Figure 2. Minimum audible field in air at 1 ATA (surface) and in 95% He, 5% O₂ at 30 ATA (depth) and the effect on auditory sensitivity at depth with respect to auditory sensitivity at the surface. Surface data abstracted from Licklider (8).

6. Experimental evidence.

Fluur and Adolfson (10) obtained air and bone conduction thresholds on 26 divers at 1, 4, 7, and 11 ATA air. They found that air conduction thresholds were elevated by 20 to 30 dB for the frequencies of 250 to 3000 Hz. At 4000 and 6000 Hz the loss of sensitivity was only about 10 dB. If a correction for impedances of $10 \log 1/11 = 10.4$ dB is applied to their results, the high frequency loss is seen to be spurious. However, we still are faced with a 10 to 20 dB loss at frequencies up to 4000 Hz, which is not explained on the basis of the foregoing analysis.

Fluur and Adolfson also found that bone conduction sensitivity was unaffected at depth. Since bone conduction receivers are closely coupled to the head, the transfer of energy to the skull is not affected by the ambient atmosphere. Assuming that bone conduction tests were performed under the same ambient noise conditions as the air conduction tests, the Fluur and Adolfson bone conduction results imply that the ambient noise levels for all audiometric tests were satisfactory. Therefore, it seems clear that some reduced air conduction sensitivity did occur at frequencies below 4000 Hz in the Fluur and Adolfson experiment which is unaccounted for by the wavelength model. The authors state that the results may be explained by disturbances of sound conduction through the middle ear.

Farmer, Thomas, and Presslar (12) obtained audiograms on six divers at various pressures in HeO₂. They found conductive losses of about 26 dB at 250 to 4000 Hz after divers had been at 19 ATA for six days. At higher frequencies the losses were smaller. When corrected for the impedance of the medium

TABLE I.

FREQUENCY Hz	OBSERVED HEARING LEVEL dB	CORRECTED HEARING LEVEL dB
250	31	19
500	30	18
1000	23	11
2000	20	8
3000	20	8
4000	16	4
6000	4	(-8)
8000	2	(-15)

The negative hearing levels in parentheses in the last column indicate improved hearing at depth as compared to surface hearing levels.

(perhaps 10 dB) the low frequency losses are about 16 dB and the high frequency losses are negligible. These results are in general agreement with the rough wavelength model presented above.

Thomas, Summit, and Farmer (13) found losses of about 20 dB at 500, 1000, 3000, and 4000 Hz, no changes at 2000 Hz and 6000 Hz for divers at 1000 ft. on HeO₂. Corrected for the impedance of the breathing mixture, the results are 8 dB losses at 500, 1000, 3000, and 4000 Hz, and hearing gains of 12 dB at 2000 and 6000 Hz. The results at 2000 Hz are quite unexpected and, at present, inexplicable. The enhanced sensitivity at 6000 Hz is predicted by the wavelength model.

The latter authors also found that bone conduction sensitivity was not greatly changed at depth. They measured a 2 to 3 dB loss of bone conduction sensitivity at all frequencies but the loss did not vary with depth below the surface. Again, the bone conduction results imply that ambient noise levels were satisfactory during the audiometric tests.

Other studies done in mixed gas environments include those by Oliver and Demard (14) and Appaix and Demard (15). Interestingly, Appaix and Demard found conductive type losses of 15 to 25 dB at 1000 Hz and below but no change in sensitivity at 1500 Hz and above at 26 ATA (n=4). At 41 ATA this pattern repeated, but some high frequency losses also appeared. Since these latter losses were accompanied by bone conduction losses, it is probable that the divers had incurred some noise induced TTS during the dive. During audiometric tests, however, the ambient noise level was about 35 dB. The authors hypothesized that the observed hypoacusis at depth was due to changes in the impedance of the tympano-ossicular system.

If the data for 26 ATA are valid, Appaix and Demard actually measured an improvement in hearing sensitivity at 1500 Hz and above (corrected for impedance). Given the Thomas, Summit, and Farmer results at 2000 Hz, this result suggests that the transition from impaired to improved hearing at depth may occur at a lower frequency than the model suggests.

At NSMRL, audiograms have been obtained during several mixed-gas saturation dives which, while not entirely satisfactory because of ambient noise problems, tend to show similar patterns of depth-related reversible conductive losses at the lower frequencies in hyperbaric environments.

More to the point concerning hearing-conservation, two pilot studies at NSMRL have shown that noise-induced temporary auditory-threshold shifts are smaller at depth than at the surface for comparable noise exposures. The results of one of these pilot studies done in compressed air at 3 ATA indicated that the reduced magnitude of the noise-induced threshold shifts was accounted for by the difference between the characteristic impedances of the two exposure media.

The results of the studies reviewed in this paper are not entirely explained on the basis of the wavelength dependant mechanisms outlined above. However, the experimental evidence is consistent with the model in that auditory sensitivity is generally poorer in mixed-gas hyperbaric environments than it is at the surface for frequencies up to 4000 to 6000 Hz. The loss of sensitivity may be about 10 dB smaller than reported because previous authors have neglected to apply a correction for the impedance of the medium to their data. Nevertheless, for frequencies up to 4000 Hz, hearing by air conduction seems to be less sensitive in both compressed air and mixed-gas hyperbaric environments. Molvaer has noted that the altered audiometric functions at depth show that the use of the dB(A) scale in assessing noise hazards in hyperbaric environments is clearly inappropriate (16).

It is important to note that in mixed-gas environments auditory sensitivity appears to be enhanced at high frequencies. Since high frequency noise has damaging effects on hearing at frequencies not usually measured in routine audiometry, high-frequency monitoring audiometry in connection with hearing-conservation programs for divers is indicated.

Since both the simple wavelength model and the available data indicate that the audiometric function is dramatically altered in hyperbaric conditions, it seems clear that existing hearing-conservation standards for noise exposure at 1 ATA are inappropriate for application to hyperbaric environments.

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Item 20-continued

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